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New data on Archean alkalic intrusions in northwestern Ontario and northern Minnesota[1]

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Abstract: Field observations and major- and trace-element geochemical data are presented for Neoarchean alkalic intrusions of the Quetico metasedimentary belt in northwestern Ontario and northern Minnesota. The intrusions are characterized by high total alkalis ($Na_2O + K_2O$) (up to 13 weight per cent) for a given SiO_2 content and show enrichment in large-ion lithophile elements and light rare-earth elements, and varied depletion in high field-strength elements. They include silica-undersaturated units. The differentiation history of the intrusions involves fractionation of clinopyroxene, hornblende, feldspar, Fe-Ti oxides, apatite, and titanite. The Blalock intrusion can also be classified as part of the sanukitoid suite. Other intrusions in the study are more evolved, with distinct alkalic affinities.

Résumé : On présente des observations de terrain et des données géochimiques pour les éléments majeurs et les éléments traces contenus dans les intrusions alcalines néoarchéennes dans la ceinture de roches métasédimentaires de Quetico dans le nord-ouest de l'Ontario et le nord du Minnesota. Les intrusions sont caractérisées par des concentrations élevées d'alcalis ($Na_2O + K_2O$) (jusqu'à 13 % en poids) pour une teneur donnée en SiO_2 et indiquent un enrichissement en éléments lithophiles à gros ions et en éléments de terres rares légers, ainsi qu'un appauvrissement varié des éléments à fort effet de champ. Ils comprennent des unités sous-saturées en silice. L'historique de la différenciation des intrusions comprend le fractionnement du clinopyroxène, de la hornblende, du feldspath, des oxydes Fe-Ti, de l'apatite et de la titanite. L'intrusion de Blalock peut également être classée comme faisant partie du cortège sanukitoïde. D'autres intrusions observées dans cette étude sont plus évoluées et comportent des affinités alcalines distinctes.

[1] Contribution to Western Superior NATMAP Project

INTRODUCTION

Late syn- to post-tectonic Archean alkalic intrusions are common in the western Superior Province in the border region between northwestern Ontario and northern Minnesota (Boerboom, 1994; Hattori and Percival, 1999; Lassen et al., 2000a, b) (Fig. 1). The alkalic intrusions were emplaced into turbiditic metasedimentary rocks of the Quetico Subprovince, which were deposited <2696 Ma (Davis and Corfu, 1995) and are cut by granitic dykes ranging from 2670 to 2665 Ma (Percival and Sullivan, 1988). A study was initiated in 1998 to better understand the petrogenesis and tectonic setting of the alkalic intrusions of the western Quetico Subprovince. During the 2000 field season the study area was extended both within Canada and south to include intrusions from northern Minnesota.

A suite of Neoarchean monzodiorite intrusions from greenstone belts of the western Superior Province have been termed 'sanukitoid' on the basis of its similarity in bulk chemical composition to high-Mg andesite from Japan known as 'sanukite' (Stevenson et al., 1999, and references therein). The term was first used for Archean plutonic rocks by Shirey and Hanson (1984); later the geochemical characteristics of sanukitoid rocks were defined by Stern et al.(1989) and Stern and Hanson (1991), which led to a discussion as to whether this is an appropriate term (Bédard, 1990). A progressive change in mantle-derived magma types occurred after the main Neoarchean accretion and deformation in the western Superior Province, starting with the calc-alkalic to slightly alkalic sanukitoid suite, and ending with alkalic suites of syenite, nepheline syenite, and rare carbonatite compositions (e.g. Stevenson et al., 1999).

In this paper we describe the field characteristics and geochemical composition of three Neoarchean intrusions from the western Quetico Subprovince including one sanukitoid suite, and discuss characteristics of sanukitoid and alkalic rocks in the Superior Province.

GEOLOGY

Several Neoarchean intrusions with alkalic affinity have been described from the Quetico metasedimentary Subprovince (Boerboom, 1994; Hattori and Percival, 1999; Lassen et al., 2000a) (Fig. 1). Collectively, they are characterized by high total alkalis (up to 13 weight per cent) at a given SiO_2 content (Fig.) and by enrichment in large-ion lithophile elements (LILE) and light rare-earth elements (LREE). The intrusions included in this study are North Elbow Lake, South Elbow Lake, Harnett Lake, Beaverhouse Lake, Whalen Lake, Kawene Lake, South Kawene, Heward, Surprise Lake, Samuels Lake, Blalock, Gheen, and Linden (Fig. 1), many of which have already been described in some detail (Lassen et al., 2000a, and references therein). Both silica-undersaturated and silica-saturated units are present, but most rocks are nepheline-free or quartz-bearing. Principal rock types include 1) undersaturated mafic rocks; 2) hornblendite and hornblende-pyroxenite; 3) alkali syenite; and 4) silicocarbonatite and carbonatite. These rocks share some characteristics with Neoarchean shoshonitic rocks from greenstone belts of the western Superior Province, such as relatively high Al_2O_3, high total alkalis, high LILE, and low high-field-strength elements (HFSE). Currently, age determinations are available for only a few intrusions, which makes statements about genetic association between intrusions tenuous. Titanites from the Harnett Lake and

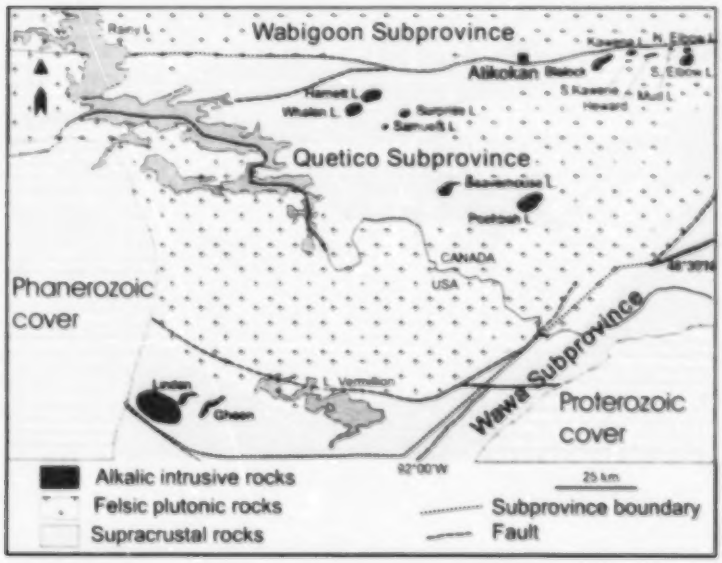

Figure 1.

Simplified geological map of part of the western Superior Province (modified from Stern et al., 1989), showing locations of the studied intrusions.

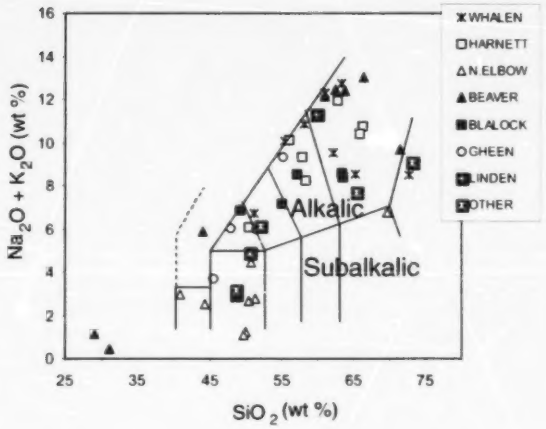

Figure 2. *Total alkali versus silica diagram for intrusions included in this study.*

Whalen Lake intrusions have yielded U-Pb concordia ages of 2680 ± 1 Ma (V. McNicoll, unpub. data, 1999), and zircons from quartz monzonite of the Blalock intrusion yielded a U-Pb age of 2688 ±4 Ma (Davis et al., 1990). Age determinations are underway for other intrusions to better constrain the timing of magmatic events in the study area.

The intrusions are similar in relative timing with respect to regional deformation; they share lithological, mineralogical, and compositional characteristics and may be petrogenetically related. They are presented as a group in chemical diagrams (Fig. 2, 3, 4).

FIELD DESCRIPTIONS AND GEOCHEMISTRY

Blalock intrusion

The Blalock intrusion has been classified as being of sanukitoid affinity by Stern et al.(1989) and Stern and Hanson (1991); further descriptions are presented in Smith and Williams (1978). Rock types range from hornblende-clinopyroxenite to syenite, but intermediate rock types are dominant. The margin consists of syenite and the interior is clinopyroxenite and rare tonalite. A strong foliation is present locally and cognate xenoliths and metasedimentary enclaves occur in the felsic units. The rocks contain clinopyroxene, hornblende, plagioclase, K-feldspar, quartz (in the felsic units), biotite, titanite, and apatite. Epidote and carbonate are common alteration products of mafic minerals.

In major-element plots (Fig. 3), the samples define curved trends suggesting differentiation through fractional crystallization. Total alkalis (K_2O+Na_2O) range from 6.9 to 8.6 weight per cent and increase with decreasing MgO as a measure of the degree of evolution. Because it is less affected by assimilation of sialic crustal material, MgO was chosen as a differentiation index over SiO_2. The content of CaO decreases steadily from 6.9 to 2.8 weight per cent, which might be attributed to fractionation of clinopyroxene, hornblende, or calcic plagioclase. Contents of FeO and TiO_2 decrease with decreasing MgO, pointing to fractionation of Fe-Ti oxides and possibly titanite, the latter being a prominent mineral in hand specimen. Contents of P_2O_5 and LREEs decrease systematically from 0.9 to 0.2 weight per cent P_2O_5 and 243 to 124 ppm Ce with decreasing MgO, suggesting apatite fractionation throughout the differentiation interval. Mafic inclusions are common in the marginal syenite and have slightly lower CaO, Al_2O_3, and Na_2O and significantly lower FeO and TiO_2 contents relative to other rock types at comparable MgO contents. Their K_2O/Na_2O are 2.5, in contrast to other units from the Blalock intrusion with ratios of approximately 1.

Linden intrusion

The Linden intrusion is located in northeastern Minnesota just north of the Quetico–Wawa Subprovince boundary (Fig. 1). It is approximately 150 km^2 on the basis of interpretation of aeromagnetic data (Boerboom, 1994), and consists of a main circular body and a smaller satellitic body, which is elongated southeast-northwest. The rocks are homogeneous and compositionally uniform syenite, but more mafic syenitic units occur locally (T. Boerboom, pers. comm., 2000). In contrast to most of the intrusions of alkalic affinity, these rocks lack cumulate textures. A moderate to strong igneous foliation is defined by the preferred orientation of clinopyroxene and K-feldspar. The syenite consists of pleochroic clinopyroxene, K-feldspar, plagioclase, titanite, Fe-Ti oxides, hornblende, biotite, and apatite. Biotite, euhedral apatite, and titanite occur as inclusions within clinopyroxene, which suggests early crystallization of these phases. The Linden intrusion is the most potassic intrusion documented in the Quetico belt, with approximately 7.5 weight per cent K_2O and with K_2O/Na_2O between 1.7 and 1.9. It is also characterized by high Ba (up to 4737 ppm) and Sr (up to 2260 ppm) contents.

Gheen intrusion

The Gheen intrusion near Linden, Minnesota (Fig. 1), ranges in composition from pyroxenite to monzosyenite, has varied mineral assemblages and textures, and generally exhibits random orientation of mineral grains. It is approximately 15 km^2 and elongated southeast-northwest. The rocks consist of characteristic zoned clinopyroxene and acicular hornblende, with K-feldspar, titanite, apatite, epidote, opaque minerals, and carbonate. The differentiated parts of the intrusion are characterized by megacrysts of K-feldspar (up to 4 cm by 1.5 cm); K-feldspar megacrysts also occur in rare enclaves of pyroxenite. Crosscutting relationships between mafic and more evolved units suggest contemporaneous emplacement of these units.

In major-element plots, the samples define curved fractionation trends when treated as a group and follow approximately the same trends as other intrusions included in this study (Fig. 3). The content of SiO_2 increases from 45 weight

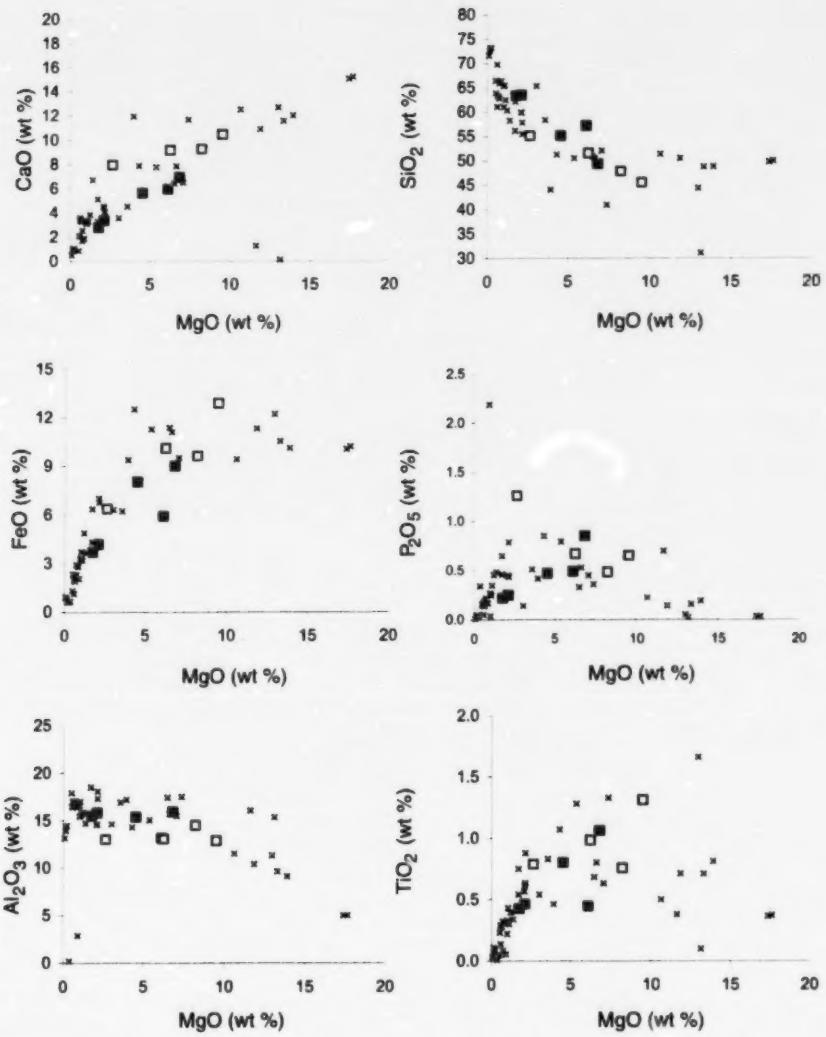

Figure 3. *Major-element variations for Neoarchean intrusions of the Quetico Subprovince. Black squares = Blalock intrusion; white squares = Gheen intrusion; black crosses = other intrusions in this study.*

per cent to 55 weight per cent and contents of FeO, TiO_2, and CaO decrease with decreasing MgO, as a measure of the degree of differentiation, pointing to fractionation of clinopyroxene, hornblende, and biotite or Fe-Ti oxides. Total alkalis (K_2O+Na_2O) increase with increasing differentiation as measured by decreasing MgO content, but there is no systematic increase for K_2O and Na_2O individually. The content of P_2O_5 increases from 0.7 to 1.3 weight per cent with evolution, indicating that apatite is not a fractionating phase of this intrusion. The Gheen intrusion is rich in hornblende in contrast to the Linden intrusion, which has clinopyroxene as the dominant ferromagnesian phase. The common occurrence of hornblende suggests that the magma was hydrous and crystallized at relatively low temperatures, although water might have been introduced at shallow levels. A mafic rock from the Gheen intrusion with high MgO (>8 weight per cent) and Cr (289 ppm) contents is also characterized by high Ba (1432 ppm), Sr (700 ppm), and K_2O (4.5 weight per cent) contents. For comparison, a feldspar cumulate is relatively rich in MgO (2.6 weight per cent) and Cr (40 ppm) and contains high K_2O (6.6 weight per cent), Ba (5808 ppm), and Sr (3125 ppm) contents.

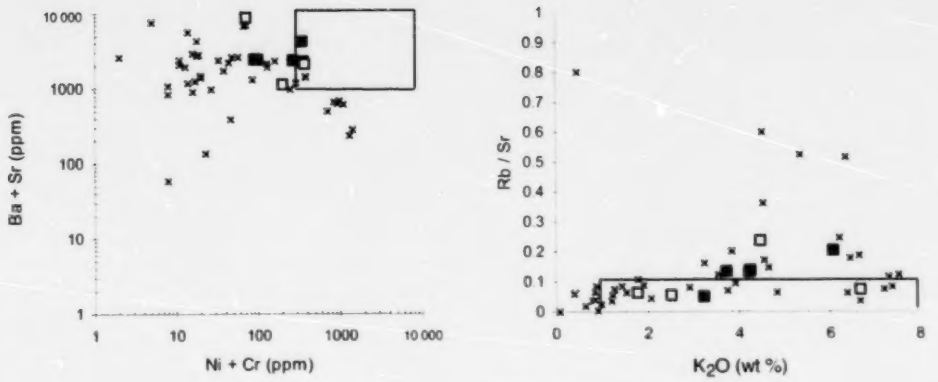

Figure 4. *Sanukitoid discrimination diagrams. The field for sanukitoid is indicated by boxes. See text for explanation. Black squares = Blalock intrusion; white squares = Gheen intrusion; crosses = other intrusions in this study.*

DISCUSSION

The term 'sanukitoid' has been defined by Stern et al. (1989) as referring to rocks containing between 55 and 60 weight per cent SiO_2, with Mg >0.6, Ni >100 ppm, Cr >200 ppm, K_2O >1 weight per cent, Rb/Sr <0.1, Ba >500 ppm, Sr >500 ppm, enrichment in LREEs, and no or minor Eu anomalies. The term 'sanukitoid suite' includes more evolved rocks derived from sanukitoid through fractional crystallization (Stern et al., 1990). Rocks formed by processes similar to those of sanukite may have chemical compositions outside the sanukitoid field (*see* Tatsumi, 1981). Alkalic rocks do not have a strict definition, but the term generally refers to rocks containing high alkali contents at a given SiO_2 content as indicated in the total alkali versus silica plot of Irvine and Baragar (1971). Following the Irvine and Baragar classification diagram, sanukitoid rocks are alkalic if they contain more than 5.0 to 5.5 weight per cent total alkalis, since SiO_2 levels are between 55 and 60 weight per cent. Most sanukitoid rocks in the western Superior Province are alkalic according to this definition.

The Blalock intrusion is not a sanukitoid *sensu stricto*, because some units have lower Ni and Cr and higher SiO_2 and Rb/Sr. However, the most mafic units fall within the sanukitoid field as defined by Stern et al.(1989) and the intrusion is of sanukitoid affinity. Figure 4 shows Ni+Cr versus Ba+Sr and K_2O versus Rb/Sr, as well as the sanukitoid field. For the Blalock intrusion, Ni content ranges from 35 ppm to 142 ppm and Cr content, from 53 ppm to 226 ppm; Rb/Sr ranges from 0.05 to 0.2, K_2O is between 3.2 and 6.1 weight per cent, Ba content is between 1221 ppm and 2282 ppm and Sr content, between 902 ppm and 1968 ppm. The LREE content ranges from approximately 200 to 500 times chondritic values. The Blalock intrusion is approximately 8 Ma older than the dated alkalic intrusions of this study. It differs from most sanukitoid bodies of the western Superior Province, which occur in metavolcanic subprovinces, in being hosted by metasedimentary rocks of the Quetico Subprovince.

Most units of the Gheen intrusion are too low in silica (45–55 weight per cent), Ni (29–84 ppm), and Cr (40–289 ppm) to be classified as sanukitoid, but fit all other criteria of the definition. Other intrusions within this study do not fit the sanukitoid classification.

The studied intrusions show a large range in composition, from ultramafic, such as the North Elbow Lake intrusion, to highly evolved syenitic intrusions, such as the Harnett Lake intrusion. The Blalock intrusion is intermediate and follows the general trend as defined by all intrusions in this study. This may imply that sanukitoid bodies need not represent primitive, unfractionated magmas.

A progressive change in magma types has been noted by many researchers in the Wabigoon and Wawa subprovinces of the western Superior Province (e.g. Card, 1990). The tholeiitic and calc-alkalic volcanism and tonalite-trondhjemite-granodiorite plutonism characteristic of greenstone subprovinces terminated by ca. 2700 Ma. This was followed the by intrusion of calc-alkalic to slightly alkalic sanukitoid suites at ca. 2690 Ma, formed by relatively large degrees of melting of a LILE-enriched upper mantle (Shirey and Hanson, 1984). Alkalic suites intruded at ca. 2680 Ma range from syenite to nepheline syenite and rare carbonatitic compositions, and their parental magmas formed by smaller degrees of partial melting of a LILE-enriched upper mantle. The involvement of a deeper asthenospheric source in the petrogenesis of these late mantle-derived magmas has been inferred by many workers (e.g. Stevenson et al., 1999). The involvement of a sublithospheric source is indicated by the Beaverhouse Lake intrusion, which is distinct in its lack of negative Nb-Ta anomalies in primitive-mantle-normalized diagrams. Instead, its chemical

characteristics resemble those of present-day ocean-island basalts and imply that it is related to hot spots (Hattori and Percival, 1999). The upwelling of asthenospheric mantle could have provided heat for extensive magmatism in the southwestern Superior Province by melting of metasomatized lithospheric mantle.

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